Window opening behaviour: simulations of occupant behaviour in residential buildings using models based on a field survey

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Abstract

Window opening behaviour has been shown to have a significant impact on airflow rates and hence energy consumption. Nevertheless, the inhabitant behaviour related to window opening in residential buildings is currently poorly investigated through both field surveys and building energy simulations. In particular, reliable information regarding user behaviour in residential buildings is crucial for suitable prediction of building performance (energy consumption, indoor environmental quality, etc.). To face this issue, measurements of indoor climate and outdoor environmental parameters and window "opening and closing" actions were performed in 15 dwellings from January to August 2008 in Denmark. Probabilistic models of inhabitants' window "opening and closing" behaviour were developed and implemented in the energy simulation software IDA ICE to improve window opening and closing strategies in simulations. The present contribution extends the knowledge about the windows control in dwellings and underlines the importance of appropriate occupant behaviour models for a better prediction of energy consumptions in buildings.

Keywords: Occupant behaviour, Energy modelling, Energy consumptions.

INTRODUCTION

Buildings account for more than 40 % of the energy consumption in the EU member states and households are responsible for consuming more than 26 % (EC, European Union energy and transport in Figures, 2006). Although residential buildings are responsible for a quarter of the total primary energy in EU members, studies with the purpose of an implementation of realistic model of human behaviour in simulation tools have been generally conducted in offices (Haldi and Robinson 2008, Rijal et al. 2007, Herkel et al. 2005).
Indeed, occupant behaviour influences the amount of energy consumed to maintain a comfortable indoor environment. However, the extent to which occupant behaviour affects building energy consumption is largely unknown. The purpose of the study was to investigate the extent of this influence.

This paper describes simulations of four building typologies, differing for ownership and ventilation type based on measurements. Simulation results are given as probabilistic distribution of values of energy consumption and indoor environmental quality depending on user behaviour has been calculated. Specifically, in this paper the research focuses on window opening behaviour in residential buildings

METHODS

A way to consider the importance of occupant behaviour in the energy simulations is explored in this work. A probabilistic approach is adopted in the simulations in order to investigate how probabilistic user patterns influence energy consumptions, improving accuracy of calculated energy performance in buildings simulation tools. The goal is to determine user behaviour patterns that describe user interaction with the controls and in particular with windows.

Based on a previous monitoring campaign in 15 Danish dwellings (Andersen RV, 2011) in Copenhagen, Denmark, a database was elaborated in order to get all the required information of occupants' interactions with controls. Using the statistical software R it was possible to determine factors with an influence on the window opening behaviour within indoor climate variables and outdoor weather conditions. Dwellings were grouped on the base of ownership (owner occupied or rented) and ventilation type (natural or mechanical). The probability of opening or closing the windows was interfered by logistic regression. A linear model described the degree of opening. Four different user behaviour patterns according to the four different building typologies were defined and they could be implemented in many existing simulation tools such as Energy Plus, Esp-r, IDA ICE, Trnsys, etc. In this paper the simulation tool IDA ICE (Indoor Climate and Energy) (IDA Manuals, 2009) was used and the equations describing the probability of user interactions with the controls of the indoor environmental quality was integrated in the program.

To be able to compare energy calculations results, simulations were conducted maintaining constant: location, building construction and heating settings.

A probabilistic distribution, instead of a single value, was preferred as a representation of energy consumptions. To do this, distribution curves were calculated with the use of twenty different lists of random numbers to associate to both the probability of opening and closing the windows. Beside energy consumptions, also indoor climate quality of the built environment needs to be taken into account and air change rates represented. Probabilistic distributions of ventilation losses are evaluated for different user type.

A PROBABILISTIC APPROACH

To estimate the effect of the control on windows by different user behaviour patterns, the probability equations determined in R were implemented in the dynamic building simulation software IDA ICE (IDA ICE Version 4.0 build 0). IDA Indoor Climate and Energy (IDA ICE) is a tool recently developed for modelling and simulating thermal comfort, indoor air quality and energy consumption in buildings. This instrument is based on a simulation platform for general modular systems, IDA Simulation Environment (Sahlin and Gronzman, 2003). Physical plant of different domains are described in the IDA using symbolic equations, formulated in Neutral Model Format (NMF) (www.equa.se) and Modelica (www.modelica.org). This makes it possible to replace and increase individual modules of the program: the

mathematical model is completely transparent to the user. All variables, equations and parameters can be controlled, and possibly replaced, to study models of behaviour.

The probabilistic model

A monitoring campaign of indoor and outdoor climate variables and occupant's control actions was conducted in 15 Danish dwellings in the period from January to August 2008 in Copenhagen (Andersen RV, 2011). Measurements were carried out in 10 rented apartments and 5 privately owned single family houses. Half of the apartments were naturally ventilated, while the other half were equipped with constantly running exhaust ventilation in the kitchen and in the bathroom. Three single family houses were naturally ventilated while the other two were equipped with exhaust ventilation. A series of variables concerning indoor and outdoor environmental conditions were monitored and meteorological data were obtained from 2 Danish meteorological stations in the dwellings proximity. Occupants' interactions with the windows (in the bedroom and living room) were monitored.
The measurements were carried out in one living room and one bedroom in each dwelling.
The following variables were measured at 10 minute intervals in all 15 dwellings.
- Indoor environment parameters:
  Temperature [°C]
  Relative humidity [%]
  CO2 concentration [ppm] (used as a proxy for IAQ)
  Illumination [lux]
- Outdoor environment parameters:
  Air temperature [°C]
  Relative humidity [%]
  Wind speed [m/s]
  Solar radiation [W/m²]
- Window state (open/closed)

The CO2 concentration was used as an indicator of the occupancy of the rooms where the measurements took place. If the CO2 concentration was below 420 ppm and the window was closed the room was classified as being unoccupied. Furthermore, if the CO2 concentration was higher than 420 ppm, but decreased and continued to decrease until reaching values below 420 ppm and the window was closed in the entire period, the room was classified as unoccupied during the period of concentration decay. The 420 threshold was based on the accuracy of the CO_2 sensors and the outdoor CO_2 concentration.
The room was classified as occupied if the window was open. This classification was based on a questionnaire survey conducted by Andersen et al. (2011) who found that the statement 'I had to leave the dwelling' was often mentioned as a reason for closing windows. If the bedroom and the living room were both unoccupied, the dwelling was classified as unoccupied. Periods when the dwelling was unoccupied were not taken into consideration in the analysis.
Danish dwellings are divided into 4 groups for the data analysis (Table 1), depending on ownership (owner-occupied or rented) and ventilation type (natural or mechanical).

Table 1. Description of groups related to the ownership and ventilation type.

Group	Ownership	Ventilation type	Number of dwelling

1	Owner-occupied	Natural	3, 4, 16
2	Owner-occupied	Mechanical	1, 10
3	Rental	Natural	6, 8, 9, 11, 12
4	Rental	Mechanical	5, 7, 13, 14, 15

In the analyses the probability of opening and closing the windows was inferred for the four behavioural models.

Users control actions was deduced by mean of logistic regression with interaction between selected variables accordingly to the following equation:

$$\log\left(\frac{P}{1-P}\right) = a + b_1 \cdot x_1 + b_2 \cdot x_2 + \ldots + b_n \cdot x_n + c_{12} \cdot x_1 \cdot x_2 + c_{13} \cdot x_1 \cdot x_3 + \ldots \quad (1)$$

Backward and forward selection based on the Akaike information criterion was used to reduce the models. The results were models able to predict probabilities of opening and closing the windows. A model that predicts the degree of opening was inferred using linear regression.

The results confirmed that there is not an always valid model to characterize the user and its behaviour, but only a suitable model according to the used database and goal of the analysis.

The outdoor temperature, indoor temperature and the indoor CO_2 concentration (used as a surrogate IAQ indicator) were the most important variables in determining the window opening/closing probability.

The four groups are divided on the basis of ownership and type of ventilation, and from the four models it appears that some common patterns of behaviour exist. In naturally ventilated dwellings, CO_2 concentration has an impact in the models of opening windows, while outdoor temperature has an impact for closing windows. In mechanically ventilated dwellings lux values are included in both the groups, whereas outdoor temperature and solar hours are being found to have an impact on the probability of closing windows.

Looking at the four groups, the three most important variables in determining the probability of opening a window were CO_2 concentration, outdoor temperature and the lux values. For the outdoor temperature and lux values, this was also the case for closing of a window, although the direction was different.

Interestingly, wind speed did not influence the behaviour in any model of the four groups.

Simulations

The aim of this study was to switch from a deterministic approach of building energy simulation toward a probabilistic one that takes into account the occupants' interactions with the building and systems. In particular the focus is on the occupants' window opening behaviour. Results of the statistical analysis provide the possibility of defining behavioural models of windows use to be implemented in simulation tool for energy simulations.

The window control was modelled probabilistic and did not follow maximum and/or minimum set-point controller for opening and closing. The probability of opening and closing the windows was calculated based on the logistic regression previously described. Specifically, four behavioural patterns were simulated.

Input parameters for simulations

The occupant behaviour equations were implemented in the simulation program using a model with a living room and a bedroom. The use of two different rooms reflected the circumstances under which the measurements were collected. A typical room is adopted for both living room and bedroom to evaluate the influence of windows control related occupant behaviour on total energy use. European Standard EN 15265/2005 "*Thermal performance of buildings – Calculation of energy use for space heating and cooling- General criteria and validation procedures*" provides a test room suitable for the simulations.

The room area was $19.8m^2$ and the dimensions are: length = 3.6m, depth= 6.5m; height= 2.8m. The external wall faced west with a window area of $3.5m^2$. The thermo physical properties of the opaque components are resumed in Table 2. The transparent component was a double pane 4.12.4 glass and its solar and thermal characteristics were: U value: 2.9 $W/(m^2K)$; solar transmittance, T= 0.7; Solar Heat Gain Coefficient, g= 0.76.

Table 2. Thermo physical properties of the opaque components

	Material	Thermal conductivity (W/(m·K))	Density (kg/m³)	Specific heat capacity (J/(kg·K))	U – value (W/m²K)	Thickness (cm)
External wall	Internal plastering	0.70	1400	0.85	0.49	0.365
	Masonry	0.79	1600	0.85		
	Insulation layer	0.04	30	0.85		
	Outer layer	0.99	1800	0.85		
Internal wall	Gypsum plaster	0.21	900	0.85	0.36	0.125
	Mineral wool	0.04	30	0.85		
	Gypsum plaster	0.21	900	0.85		
Floor covering	Acoustic board	0.06	400	0.84	0.241	0.40
	Mineral wool	0.04	50	0.85		
	Concrete	2.10	2400	0.85		
	Mineral wool	0.04	50	0.85		
	Concrete	1.40	2000	0.85		
	Floor covering	0.23	1500	1.5		
Roof	Rain protection	0.23	1500	1.3	0.438	0.284
	Insulation layer	0.04	50	0.85		
	Concrete	2.10	2400	0.85		
External floor	Concrete	2.10	2400	0.85	0.76	0.284
	Mineral wool	0.04	50	0.85		
	Concrete	1.40	2000	0.85		
	Plastic floor covering	0.23	1500	1.5		

The location was Copenhagen in Denmark (55.63° N, 12.67° E). The meteorological data used in the simulations refers to the Danish design reference year.

Both bedroom and living room were heated by waterborne radiator with a constant heating set-point of 21°C from September to June, working with a deadband of 2°C and a maximum power of 2500W placed under the windows in the two rooms. None of the zones were mechanically cooled. Cracks were added to the two rooms, inducing an average infiltration rate of respectively 0.4 h^{-1} in the living room and 0.2 h^{-1} in the

bedroom (calculated in IDA ICE). Both the living room and the bedroom had only one wall facing the exterior environment in the west orientation and only one operable window.

As internal source, one person was considered present in each of the rooms with a house living schedule (from Monday to Sunday, from 6:00 to 8:00 and from 15:00 to 23:00) at an activity level of 70 W/m^2, that is a metabolic activity of 1.2 met. The lighting schedule followed the presence of people (100%). Furthermore, the light in the room, with an emitted heat per unit equal to 50W, automatically switched on if the minimum work plane illuminance was lower than 100 Lux based on the study of the Lightswitch-2002 (Reinhart, 2004); the light was automatically switched off at an illuminance level of 500 Lux. The electrical equipment consumed 50W from 18:00 to 22:00 from Monday to Friday, and from 15:00 to 22:00 on Weekends. Solar shading was not used, as this is very rarely used in Danish dwellings (Andersen et al. 2009).

In the standard schedule windows opened if the indoor temperature exceeded a certain value (25°C ±2°C) and the outdoor temperature was lower than the indoor temperature.

According to the mechanical ventilation type of the database dwellings, two models are set differing only for the ventilation type: one model was realized for the natural ventilated buildings and another one for the mechanical ventilated building (exhaust ventilation).

A probabilistic approach for simulation

IDA Indoor Climate and Energy, as with most other simulation programs, is deterministic in nature. Therefore there is a need to translate the probability of an event (e.g. a window opening) into a deterministic signal. A way of doing this is to compare the probability of the event to a random number to determine if the event takes place or not. As the given probability is the probability of opening and closing the windows in the next ten minutes, the comparison was made with a random number that changed every tenth minute.

Based on the model of Reinhart (Reinhart, 2004) and Newsham (Newsham et al. 1995), two time series of evenly distributed random numbers of a rectangular distribution between 0 and 1 with an interval of ten minutes were loaded in the simulation program, one series for opening and another for closing. The windows were opened or closed based on a comparison of the random number with the calculated probability. If the calculated opening probability was higher than the random number, the window was opened and remained open until the closing probability was higher than the random number from the closing series. In the event that both the random open number and the random close number were smaller than the calculated probabilities, the window state remained unchanged.

Two stochastic processes were needed in order to predict the state of the window. First of all, the probability of opening the window for four user profile were determined as a function of explanatory variables in the statistical analysis. The closing probability was calculated in the same way.

Secondly, the linear model gave an indication about the degree of opening. Using the probability of opening and closing the windows, quantitatively controlled by the linear model, the degree of opening was then predicted.

The implementation of the users' behaviour models in the simulation tool IDA ICE followed the equation:

$$p = \frac{exp(a + b1x1 + b2x2 + \cdots)}{1 + \exp(a + b1x1 + b2x2 + \cdots)} \qquad (2)$$

To get an indication of the performance of the four models and their ability to predict window opening behaviour, simulations were run for each model using a simulation reference model. The results were compared to the corresponding models where a standard window control (on/off temperature control + schedule) was used. In the standard schedule windows opened if the indoor temperature exceeded a certain value (25°C ±2°C) and the outdoor temperature was lower than the indoor temperature.

RESULTS

Results are given in the form of primary energy, accordingly with the European Standard EN 15603 (2008) that establish the conversion factors as $fp_{fuel}= 1.36$ for heating and as $fp_{electricity\ mix\ UECPTE}= 3.14$ for other electric systems and appliances.
The air change rate was used as a first indicator of how much of the change in performance actually is caused by a shift in window opening behaviour. Fluctuations in air change rate were signs of a shift in the window opening behaviour governed by a change in the indoor climate large enough to influence the window opening behaviour models.
From the data reported in Table 3, the existing relationship among probabilistic windows control for the groups and air change rates, ventilation losses and energy consumption can be noted.

Table 3. Average values of air change rates, ventilation losses, space heating energy demand and primary energy for different users.

User types*	Air change rate (m³/(s·m²))		Ventilation losses (kWh/m²)		Heating, EP (kWh/m²)	Total Energy, EP (kWh/m²)
	Bedroom	Living room	Bedroom	Living room		
I	0.58	0.65	70	72	266	393
II	0.91	0.59	140	96	349	479
III	0.58	0.64	71	70	266	392
IV	0.73	1.00	112	80	321	451

* User types refer to the four groups in Table 1

A significant difference could be appreciated in the comparison between the groups with natural ventilation (I and III) and groups with mechanical (exhaust) ventilation (II and IV). Ventilation rates in the mechanical ventilated buildings were up to 57% higher than in the natural ventilated ones (for groups I and II in bedroom and for groups III and IV in living room). Major differences could be found in the ventilation losses in the bedrooms: here the groups with mechanical ventilation had losses of up to 101% more than natural ventilated buildings (bedroom, groups I and II). Looking at the space heating energy demand, the differences between groups were minor, due to the fact that the building envelope was the same for all the four groups. This was especially true for the primary energy, where lighting facilities, equipments and domestic hot water were exactly the same for all the groups.
In the tables (4 and 5) is a highlighted the comparison between the building simulated with a control of windows based on fixed rules of temperature (On/off + temperature) and the buildings modelled with a probabilistic approach.

Table 4. Air change rates, ventilation losses, space heating energy demand and primary energy for natural ventilated buildings.

User types*	Air change rate (m³/(s·m²))		Ventilation losses (kWh/m²)		Heating, EP (kWh/m²)	Total Energy, EP (kWh/m²)
	Bedroom	Living room	Bedroom	Living room		
I	0.58	0.65	70	72	266	393
III	0.58	0.64	71	70	266	392
Standard NV	0.87	0.86	77	76	281	407

* User types refer to the four groups in Table 1

Table 5. Air change rates, ventilation losses, space heating energy demand and primary energy for mechanical (exhausted) ventilated buildings.

User types*	Air change rate (m³/(s·m²))		Ventilation losses (kWh/m²)		Heating, EP (kWh/m²)	Total Energy, EP (kWh/m²)
	Bedroom	Living room	Bedroom	Living room		
II	0.91	0.59	140	96	349	479
IV	0.73	1.00	112	80	321	451
Standard MV	0.81	0.78	90	87	299	429

* User types refer to the four groups in Table 1

From the tables emerges that there were significant discrepancies between the probabilistic and deterministic approaches.

Actually, for the natural ventilated buildings (groups I and III, table 4) it appeared that the predefined-fixed control of windows produced higher air change rates than the probabilistic control: the air change rate was up to 33.8% higher in the bedrooms, while the ventilation losses were 9.9% less in the simulations where the probabilistic approach was used. Differences were less visible in the space heating energy demand and in the total primary energy , but still present as it resulted in a 5% discrepancy between the heating demand and 4% difference in the primary energy.

Table 5 is related to the simulations with mechanical exhaust ventilation. It appears clear that in this case the predefined schedule for the window control underestimate the opening and closing events compared to the probabilistic models: in the buildings modelled with the probabilistic approach, the air change rates were 33.6% higher (bedroom, group IV) than in standard model, the ventilation losses up to 54.8% more (bedroom, group II): this result perfectly fits with the existing studies on the topic, where bedrooms are the rooms were windows are most frequently opened (Fabi et al. 2011). By consequence, space heating energy demand is underestimated, and it results in buildings where the windows are controlled with a probabilistic function consume up to a 58% more energy than a building where the control on windows is regulated by a fixed schedule related to the temperature.

Distributions

A probabilistic distribution of energy consumption depending on user types was obtained by switching the random number list in the simulation program IDA ICE. Both the random numbers for opening and closing probability were substituted. All models were simulated 20 times.

The results of the twenty simulations were very similar to each other, in particular in case of the groups with natural ventilation only (group I and III), where no significant

changes appeared for both air change rate and ventilation losses, and by consequence in primary energy.

The probabilistic distribution curve reported in Fig. 1 showed that the air change rate for group IV (with exhausted mechanical ventilation) ranged from $0.87 h^{-1}$ to $1.14\ h^{-1}$ in the bedroom (variation equal to 24%). In the case of space heating energy demand this meant a range of 10 kWh/m^{2}year (ranging from 313 to 323 kWh/m^{2}year). This narrow range of variability can be attributed to the degree of opening of the windows that was very small and by consequence causing a low variability on the air change rate. Moreover, the degree of opening was calculated with a linear regression based on the measures coming from only three windows. Thus, the degree of opening issue is going to be deepened with further investigations in order to have a better description of the models.

Figure 1. Distribution of mean air change rate (a) and space heating energy demand (b) for Group IV user type.
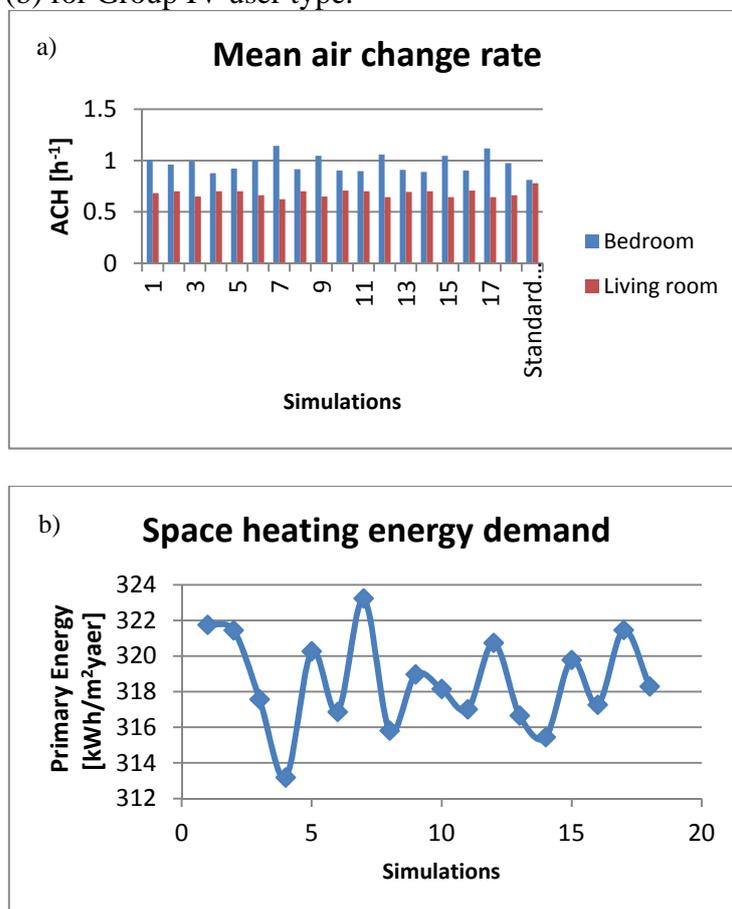
Inarguably an infinite number of scenarios could have been simulated, each different in comfort category, representing a different user profile and therefore more outcomes could have been found. Indeed the approach of this study aim to present a procedure that could be extended to both physical factors like thermal mass, percentage of transparency in the facade, shading devices, etc. and non physical factors, like social or biological factors like the lifestyle or the age. Nevertheless factors involved in the energy programs implementations can be extended to thermal mass, facade percentage of transparency, shading devices or window opening with the aim to understand

which of these have the most influence in energy use and so, constitute recommendations for improved buildings design with regard to energy reduction.

CONCLUSIONS

Since a model per definition is a description or a simplification of reality, a model for window opening behaviour can therefore only be approximated to some extent. In this paper a probabilistic approach was used to simulate the occupant behaviour related to the window opening and closing. Four window opening models were developed and implemented in IDA ICE and the performance was simulated for a bedroom and living room. The models were based on actual, measured window opening behaviour. They were derived using logistic regression analysis to infer the probability of opening or closing a window. This meant that only values leading up to the opening/closing event were included and not values influencing the window state that was to be predicted. The use of probabilistic models resulted in a large range between the groups with natural ventilation only and the groups with mechanical ventilation as well. The results of the simulations were distributions of energy consumptions and air change rates for different user types. This created distributions of energy consumptions and indoor climate performances rather than one exact value. Even if calculated consumptions in the analysed Danish dwellings do not significantly vary within them, they are definitively higher (in the case of mechanically ventilated buildings) or lower (in the case of naturally ventilated buildings) compared with the simulation results in accordance with a standard control of windows. This range of results represented the variety in window opening behaviour often found between dwellings and therefore formed a good basis improving the analysis of actual building energy performance.
Future field studies should include other aspects of occupants control on building systems in order to enhance more accurate representations of reality by simulation tools prediction methods.

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